High Field HTS R&D Solenoid for Muon Collider

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Background

- Ionization cooling in muon collider needs very high field solenoids (>30 T).
- Use of HTS is essential to generate such high fields in a non-pulsed mode.
- High Field (20 + T) HTS solenoid is being developed under two SBIR funding to Particle Beam Lasers (PBL) with BNL being a research partner in both:
  - First SBIR: ~10 T, ~100 mm i.d., ~160 mm o.d. outsert HTS solenoid.
  - Second SBIR: (a) ~12 T, ~25 mm i.d., ~90 mm o.d. insert HTS solenoid (b) integrate this with the first solenoid to possibly generate ~22 T field.
  - Beyond SBIR: Test combined unit at ~19 T NHMFL to test at fields approaching 40 T.
- This is a very aggressive proposal with challenging targets and modest funding.
- This is an experimental program. The goal is to do study systematically by building a number of coils (not just test a unit), find practical solutions, etc., etc.
- Major challenges: quench protection, large stresses, minimization of degradation, life time issues in demanding applications.

HTS Magnet Programs at BNL

- **BNL has been active in developing HTS technology for over a decades.**
- **Built over 50 coils with the first generation (1G) HTS and over 25 coils with the second generation (2G) HTS.**

- **Currently funded HTS programs:**
  - These two high field solenoids >>> **An experimental program**
  - FRIB second generation HTS quad (another talk in this session) >>> **A conservative program**
  - Superconducting Magnetic Energy Storage (25 – 30 T) >>> **High risk high reward program**
- **Previous HTS programs:**
  - Two low field solenoids to be used in R&D devices at BNL
  - RIA first generation HTS quad (a unique and successful program)
  - Common coil R&D dipoles with Bi2212 Rutherford cable (and also with HTS tape)
- **These varieties of programs help each other:**
  - In developing wider understanding by sharing resources
  - Under current projections (with all funded programs), by 2013 we should use ~50 km of HTS wire (NO TYPO), normalized to ~4 mm width tape equivalent

Basic Design Parameters
(based primarily on conductor performance)

Target Design field (optimistic)	~22 T
Number of coils (radial segmentation)	2 self supporting
Stored Energy (both coils)	~110 kJ
Inductance (both in series)	4.6 Henry
Nominal Design Current	~220 A
Insulation (Kapton or stainless steel)	~0.025 mm
J_e (engineering current density in coil)	~390 A/mm^2
Conductor	2G ReBCO/YBCO
Width	~4 mm
Thickness	~0.1 mm
Stablizer	~0.04 mm Cu

Outer Solenoid Parameter	
Inner diameter	~100 mm
Outer diameter	~160 mm
Length	~128 mm
Number of turns per pancake	~240 (nominal)
Number of Pancakes	28 (14 double)
Total conductor used	2.8 km
Target field generated by itself	~10 T
Inner Solenoid Parameter	
Inner diameter	~25 mm
Outer diameter	~90 mm
Length	~64 mm
Number of turns per pancake	~260 (nominal)
Number of Pancakes	14 (7 double)
Total conductor used	0.7 km
Target field generated by itself	~12 T
External Radial support (overband)	Stainless steel tape

- **This theoretical short sample performance is based on certain scaling.**
- **The purpose of the program is to find out what limits the actual performance; what R&D is needed to overcome those limitations and how close to short sample one can reach with available resources.**

Differences between Insert Coil and All HTS Solenoid Tests

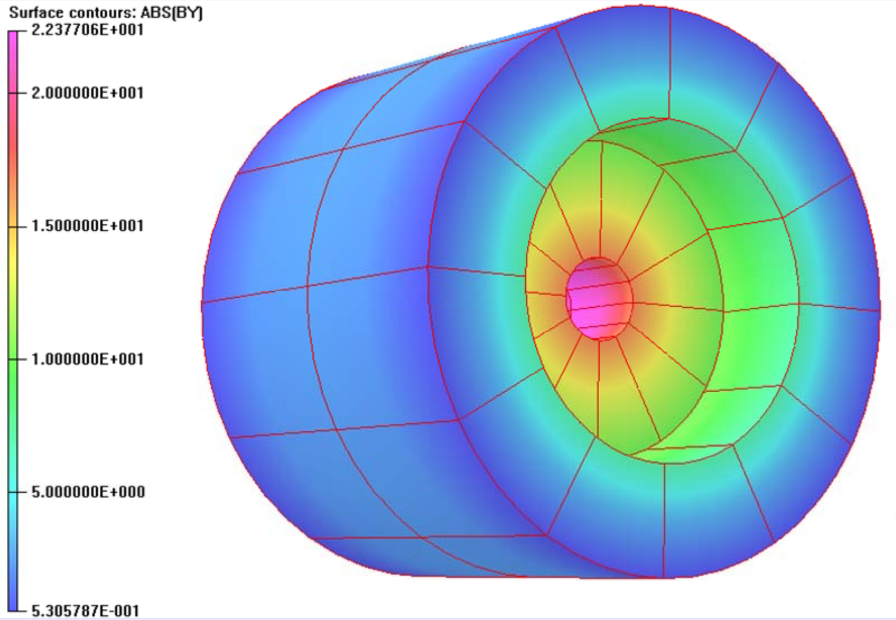
Much higher fields than 20 T have been reached in insert coil tests

- Field components are different in an all HTS solenoid and field perpendicular component is likely to limit the magnet performance
- Axial stresses on HTS coil are significantly different
  - Stress/strain of HTS tape in axial direction is different.
  - Tolerance is that direction is not well known – but it is order of magnitude worse.
  - If not defined and accommodated properly, it may limit the performance (not so in insert coil).

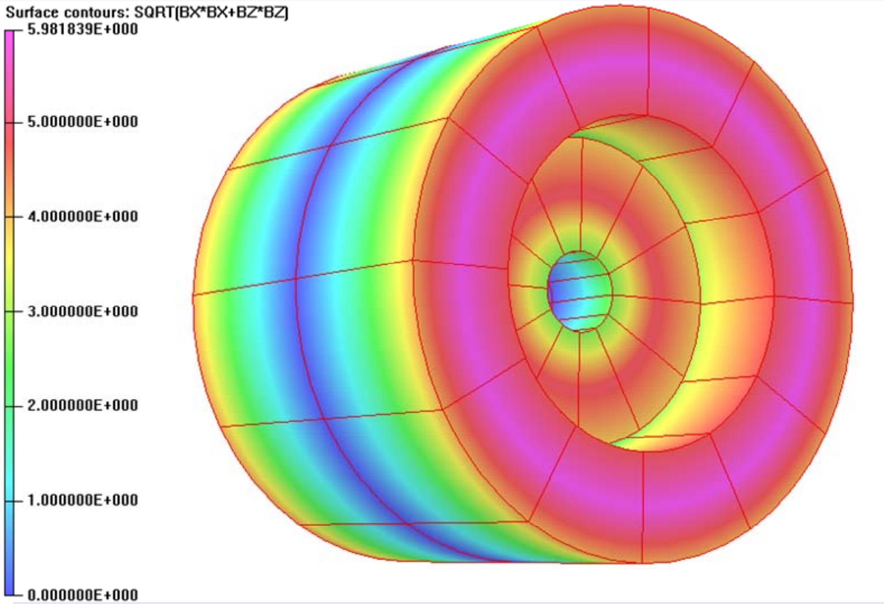
Field Components

Inner and outer coils together

Field Parallel (~22 T)



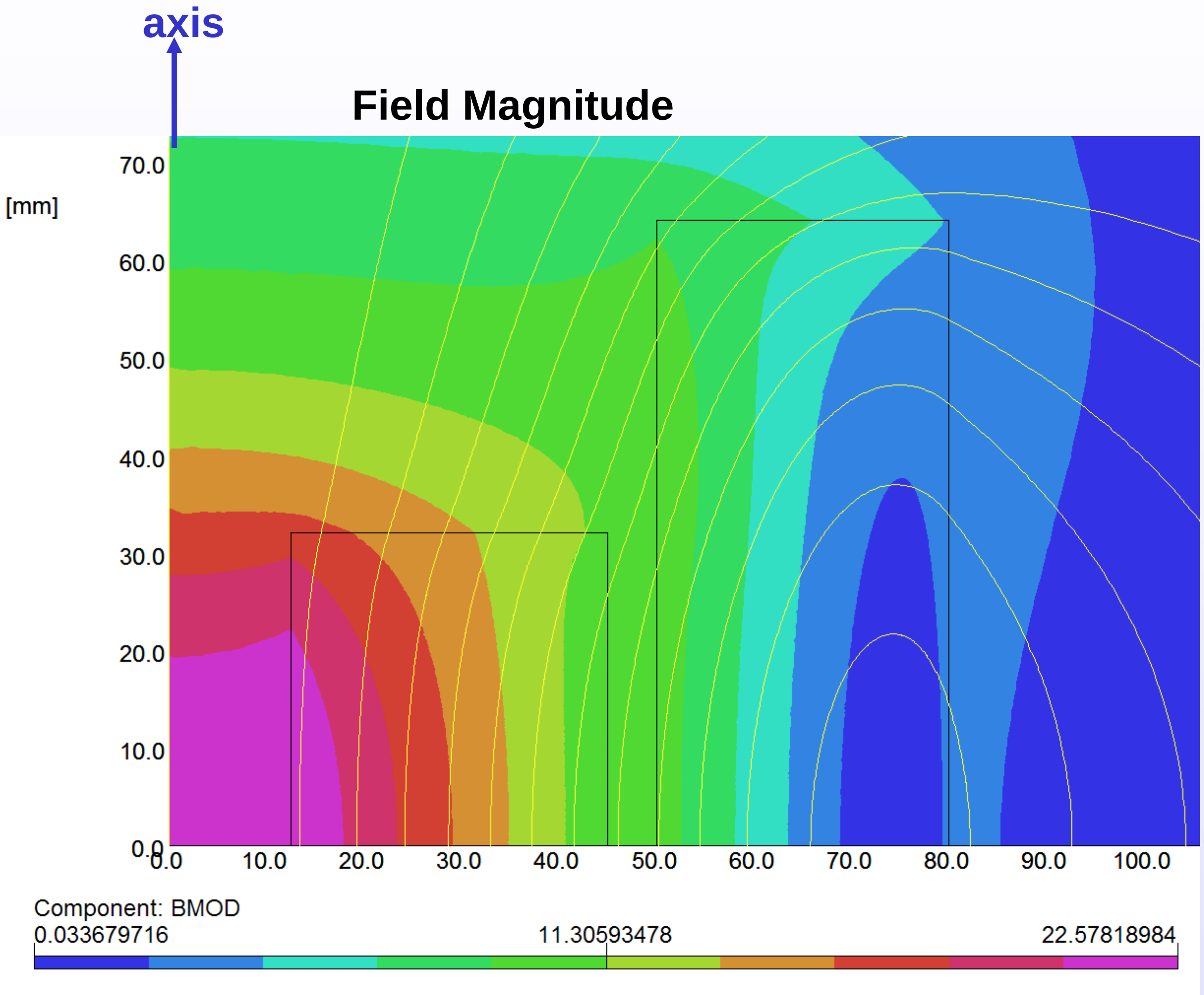
Field Perpendicular (~6 T)

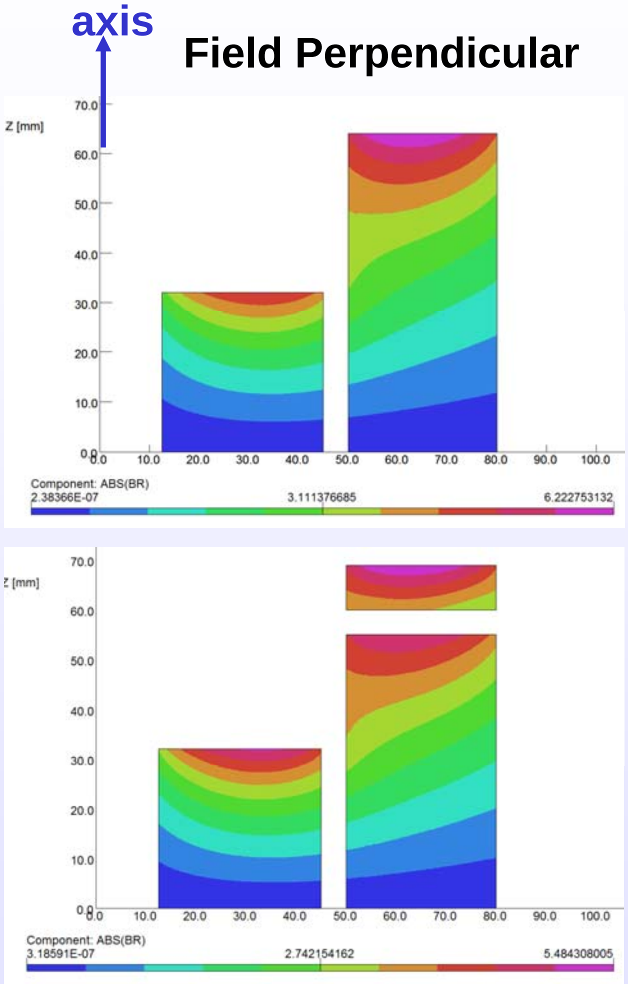


Performance may be limited by the perpendicular component

(Note: field parallel and perpendicular components are used for simplicity; for more rigorous analysis one should model the angular dependence)

Improving the Design Performance by Reducing the Perpendicular component


Field Magnitude


Field Perpendicular

5 mm spacer reduces perpendicular component by ~15%

It should also reduce the axial stress (may be critical for 2G HTS)

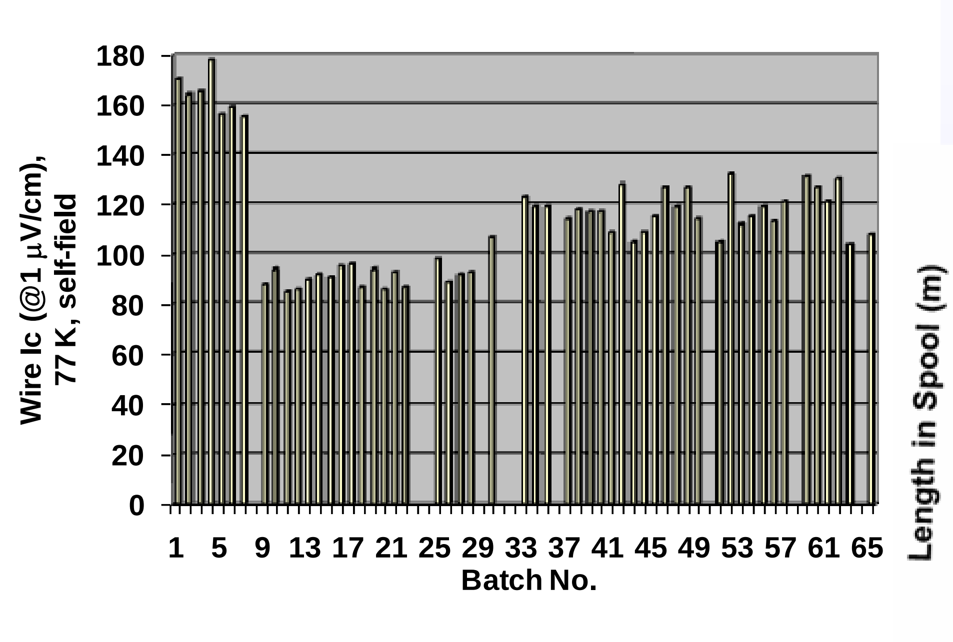
Current Status

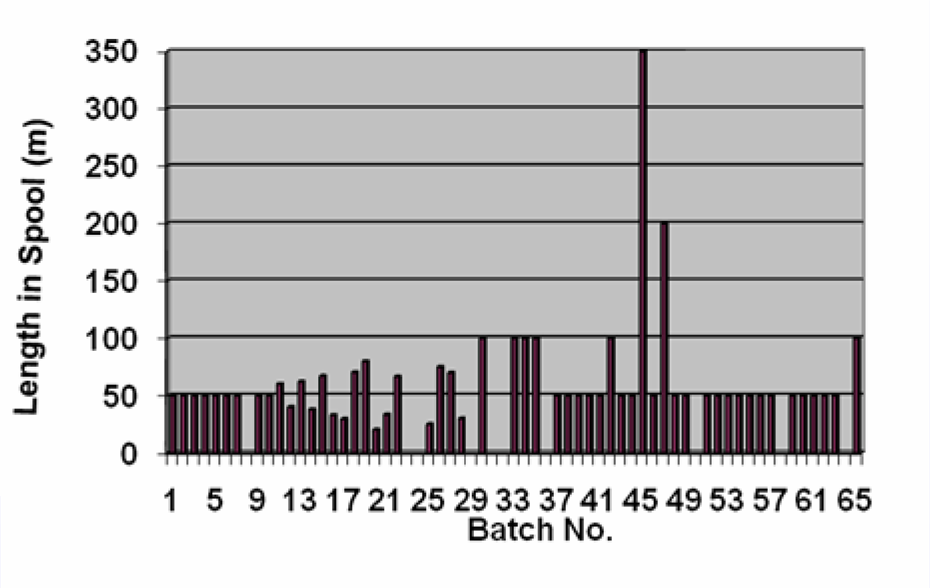
- We have received over 3 km of 4 mm 2G tape from SuperPower
- We need 28 coils for outer solenoid (each needs 100 meter tape) and 14 for inner (each needs 50 meter of tape).
- We have built 17 coils for outer solenoid with 1.7 km tape.
- All coils have been tested in LN2 and 4 in LHe
  - testing a large number of coils is important for systematic study.
- Several important lessons learnt (Shiroyanagi, this conference)

2G Tape from SuperPower

Wire was delivered in several batches.

Somewhat different Ic from batch to batch.





Each coil needs 100 meter tape. One splice per coil was allowed for cost reasons.

~100 mm dia 2G Coils

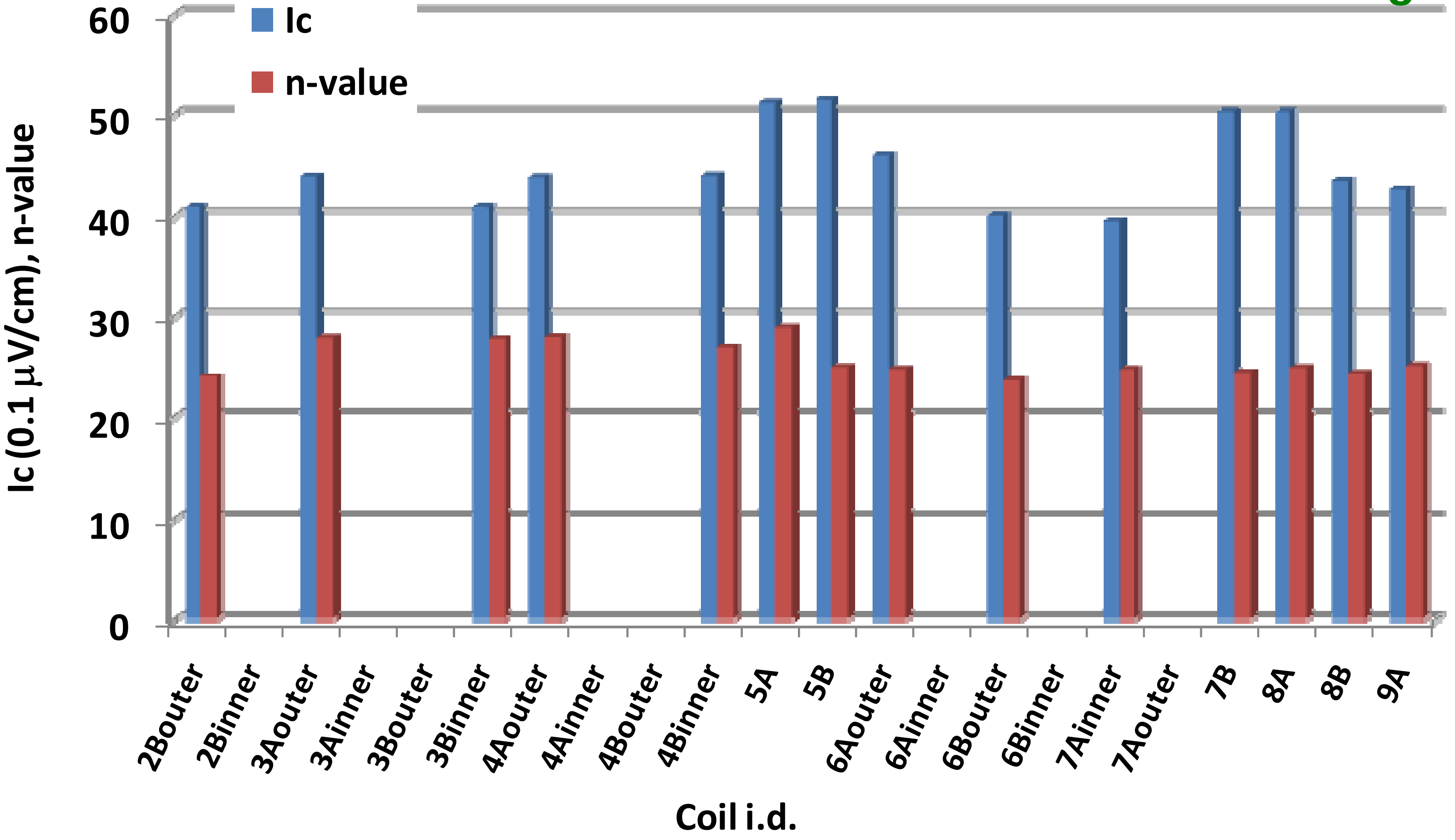
Each coil has ~240 turns and uses 100 meter tape (maximum one splice)

Lessons Learnt

- Several important lessons learnt
  - Paper by Shiroyanagi, et al. (this conference)
- Thermal shocks must be avoided as that may degrade the coil performance
- **With that precaution, several coils were built and successfully tested**
  - 2G (of today) appears to be more sensitive than 1G (got more time to mature)
  - One must be able to detect and avoid small local irregularities (which may turn in to defects) for the successful development of low temperature, high performance applications. The same conductor and coils that were OK for high temperature, low current applications, may not work under more demanding conditions here.
  - Conductor vendors are encouraged to focus on this **now** – not just on Ic, Ic, Ic.

Performance of 2G Coils in LN2

Demonstration that the care is rewarding

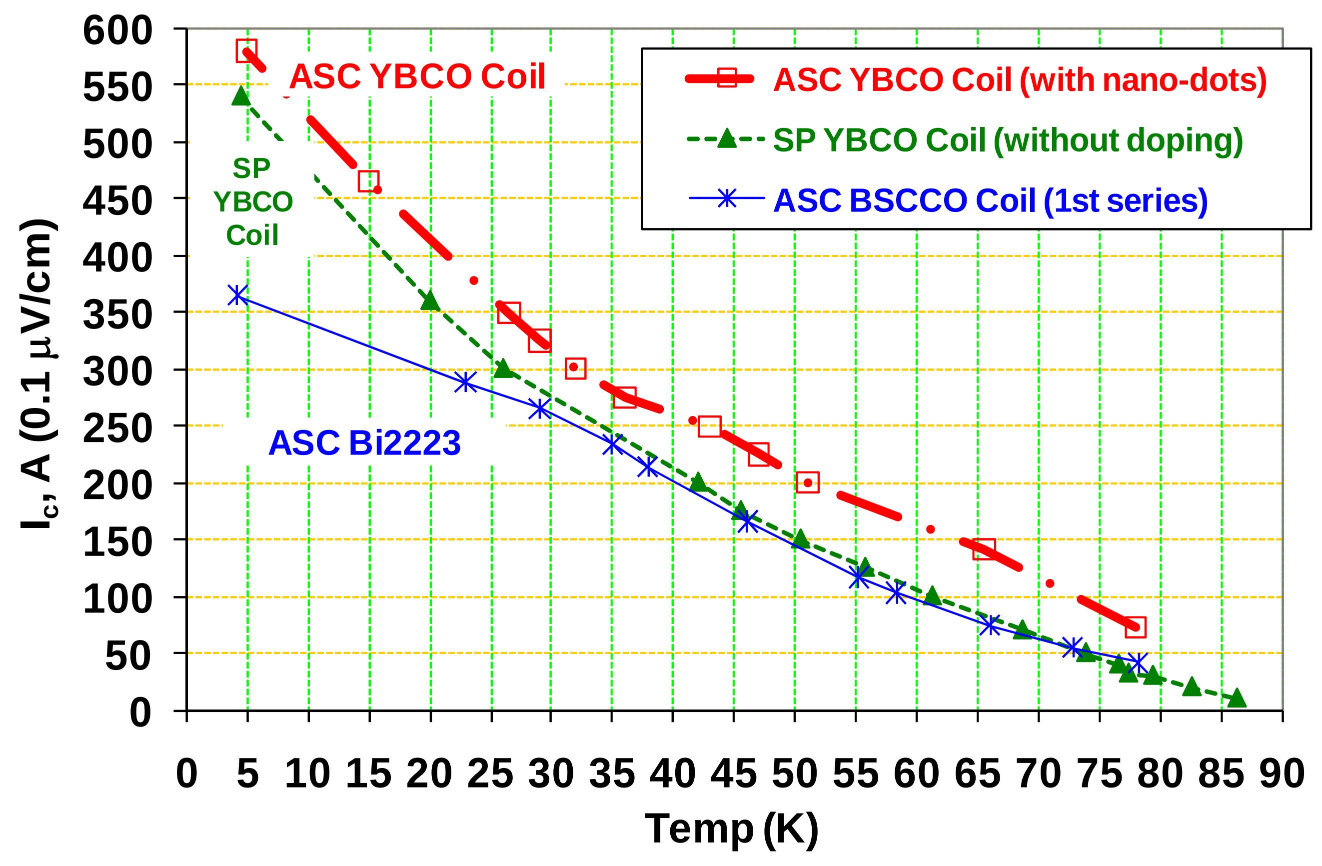


To develop technology, it is important to build and systematically test a large number of coils – real applications will follow.

Low Temp Performance of FRIB Coils
(R&D during technology development period)

During the initial FRIB R&D period, coils with 2G HTS from ASC (~0.4 mm X 0.3 mm) and SuperPower (0.4 mm X 0.1 mm) were built and tested

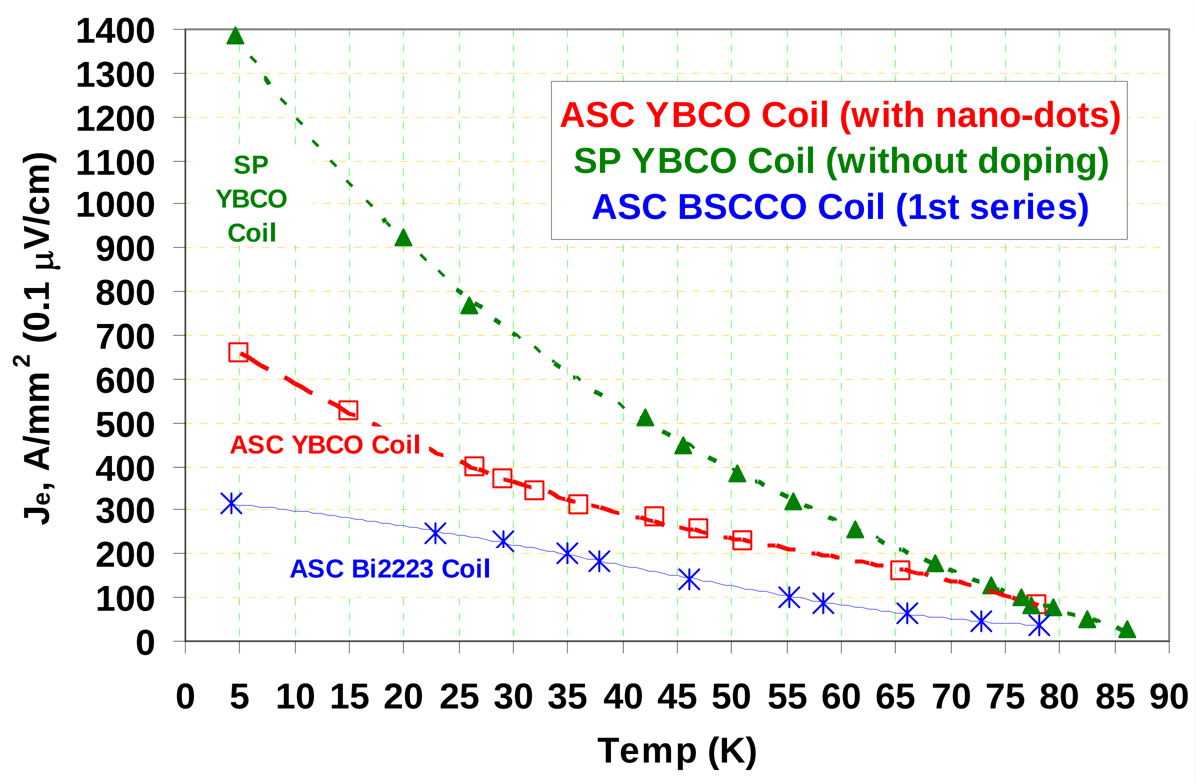
Constructed with the conductor purchased ~ 3 years ago



Low Temp Performance of FRIB Coils (R&D during technology development period)

Tape width: ~ 4 mm

Copper thickness: SuperPower ~ 0.045 mm; ASC ~ 0.1 mm



If coils to go normal (quench, thermal runaway, etc.):

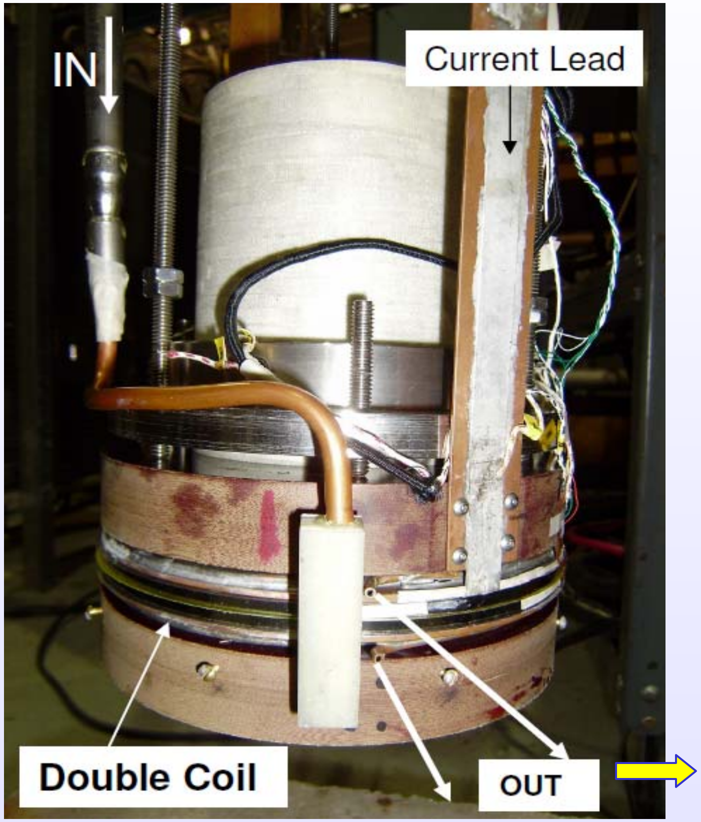
- Copper current density in ASC coil : ~1500 A/mm^2
- Copper current density in SuperPower coil : ~3000 A/mm^2

These numbers are amazing ...

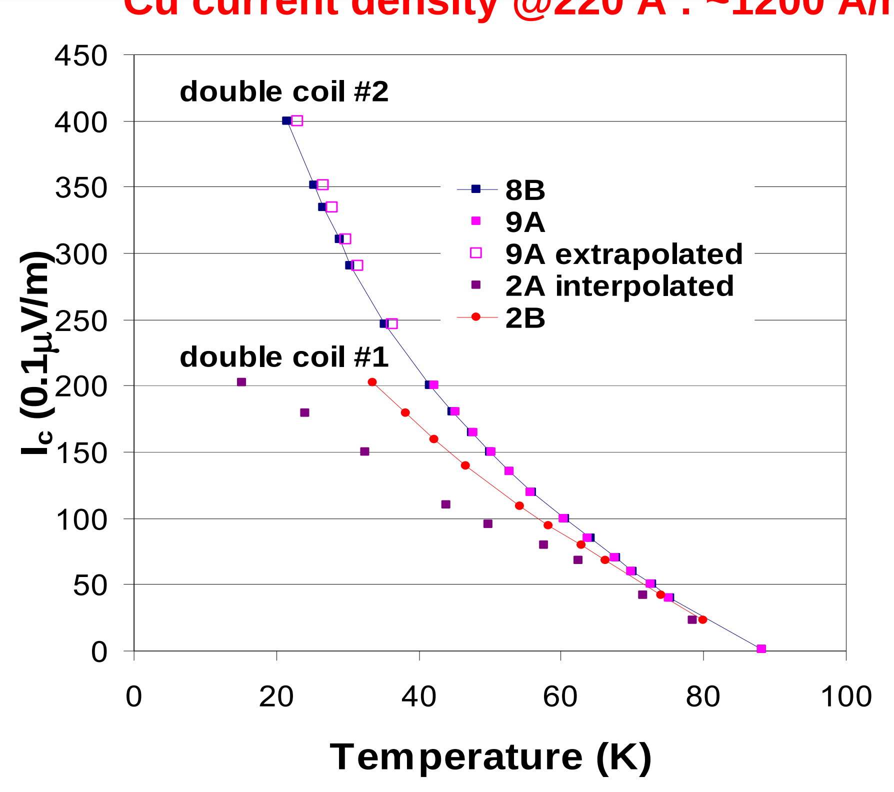
- ***May be too demanding for protection and should be avoided in real applications.***

Recent Low Temperature Solenoid Coil Test Results

Note: ~10 T or ~20 T design needs only 220 A with SuperPower Tape



Cu current density @220 A : ~1200 A/mm^2



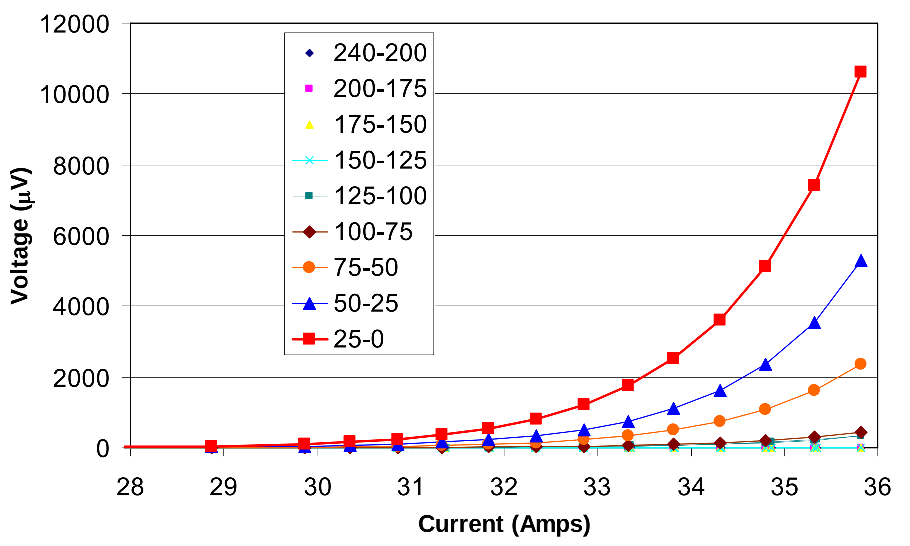
Are these high current tests too demanding in terms of protection?

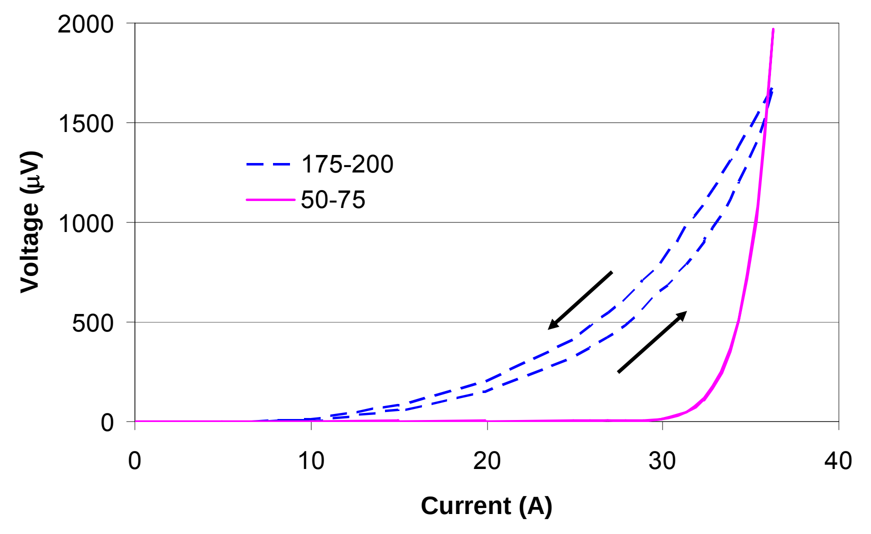
(also larger Lorentz forces at high currents)

Were we too lucky or spoiled by FRIB tests to > 500 A?

Detailed Analysis of LN2 Test Results

- Several v-taps are placed: ~25 turns per v-tap in coil with 240 turns (~10 meter/v-tap in 100 meter/coil).
- A small section of coil developed equivalent to quench voltage during the testing – this could possibly be missed when averaged over a long section before it's too late (μV/cm definition).
- There could possibly have been a small latent defect in the conductor which manifested more seriously and became active only when the circumstances were very demanding.



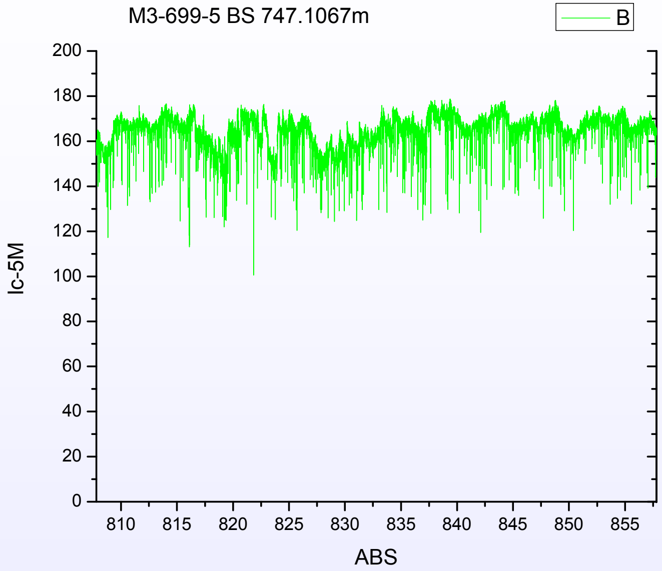


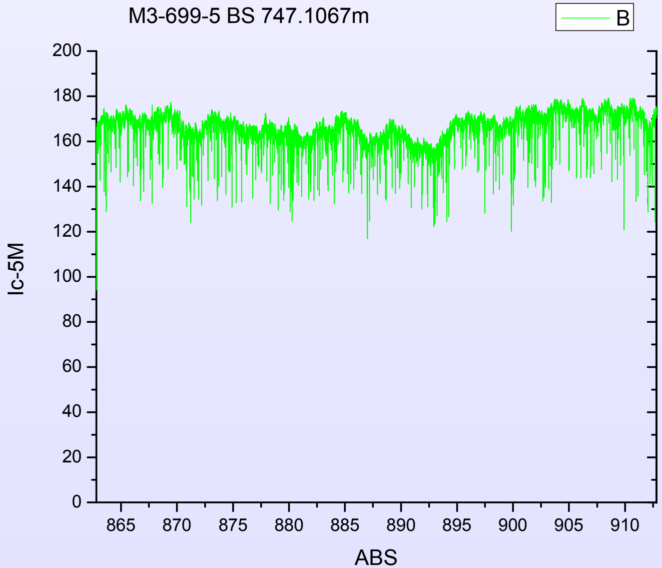
Tapestar Measurements of Ic in 1 mm interval at SuperPower

- One way to detect these small sleeping defects could be Tapestar measurements.
- There are always some weak points, however small they are, in every production of any kind.
- These minor defects may not be relevant to most applications and may become visible only under very demanding circumstances as in ultra high field magnets.

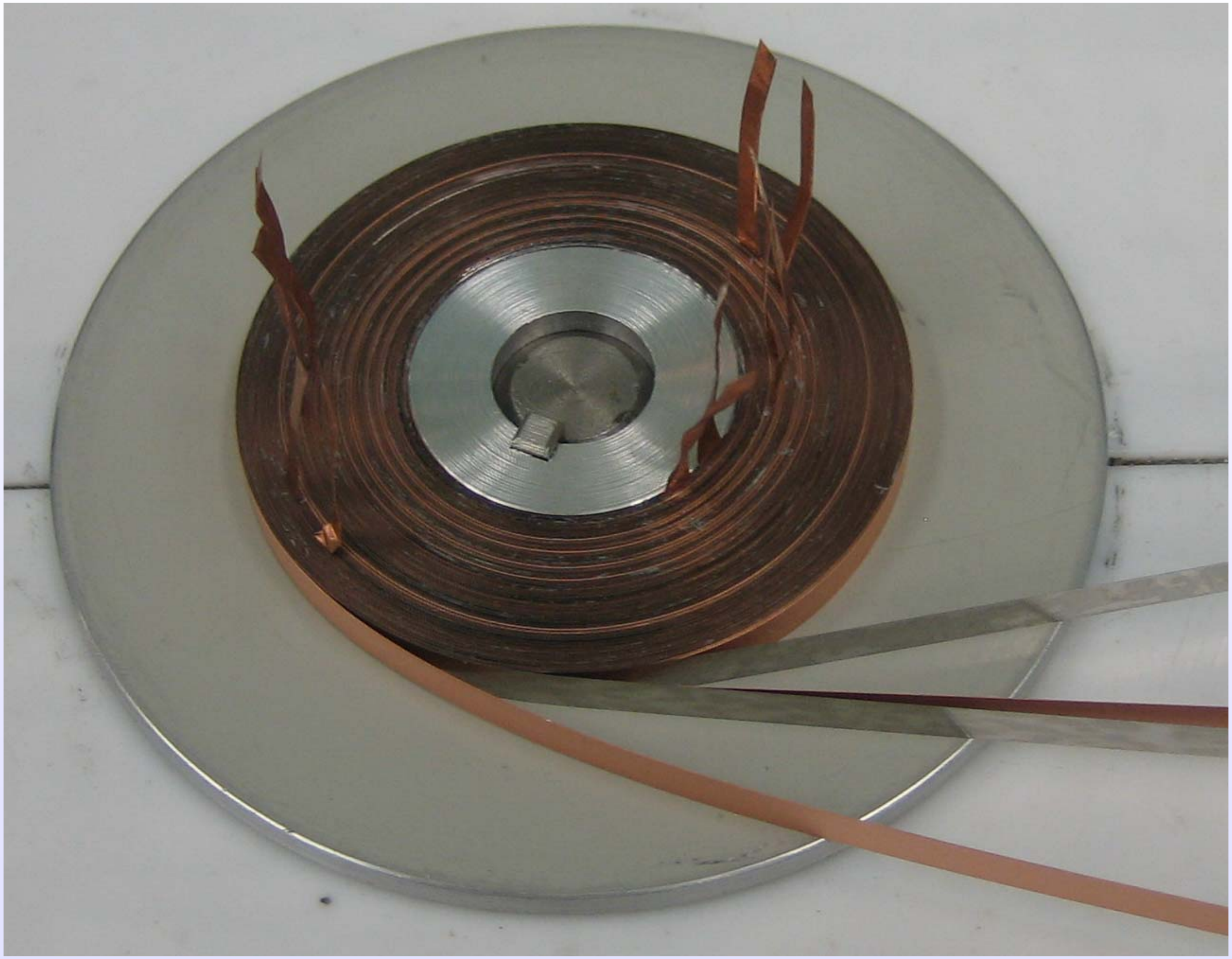
- But how can one be sure it is that? Can a weak-point in tapestar measurements be correlated to local defect developed in a coil.

- Need for an experimental program.





Experimental Coil Program at BNL



Coil i.d. ~25 mm

Coil i.d. ~50 mm

Coil types:

Bifiler and
double pancakes

Current HTS R&D at BNL

- Improved electronics for detecting small voltage signal over noise
- Quench detection, protection, etc.
- Increased instrumentation for protection

- Measurement of the impact on conductor of axial loading

- Systematic R&D with small coils on a number of topics

SUMMARY

A number of R&D program with different philosophies help each other and in the development of the overall technology

- 20+ T HTS solenoid (this program): Experimental program
- FRIB HTS quad: Conservative design for a real machine
- High energy density SMES: High risk, high reward dream

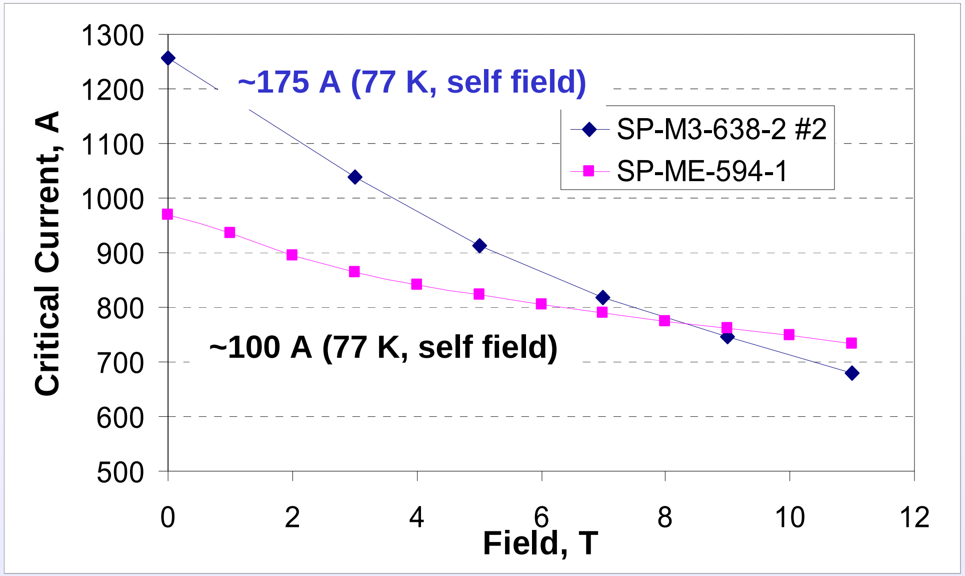
Progress and status of solenoid program

- A large number of coils (17) have been built and tested.
- Problem with thermal shock in LN2 test has been identified and managed.
- Quench protection and other R&D are underway
- Coils have been successfully tested in LHe to the required current: 220 A.

Backup slides

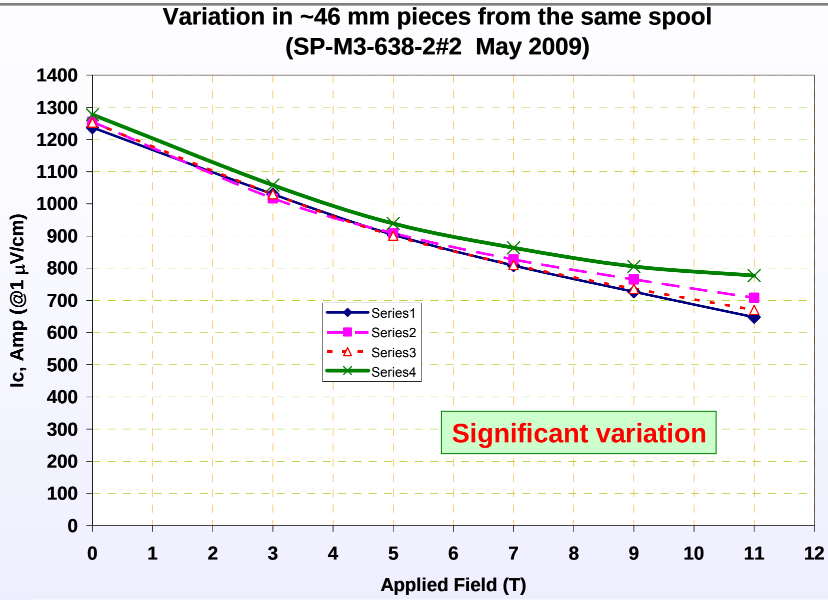
Critical Current Measurements at 4K as a Function of B// in SuperPower Wire

Two 2G wires from different time

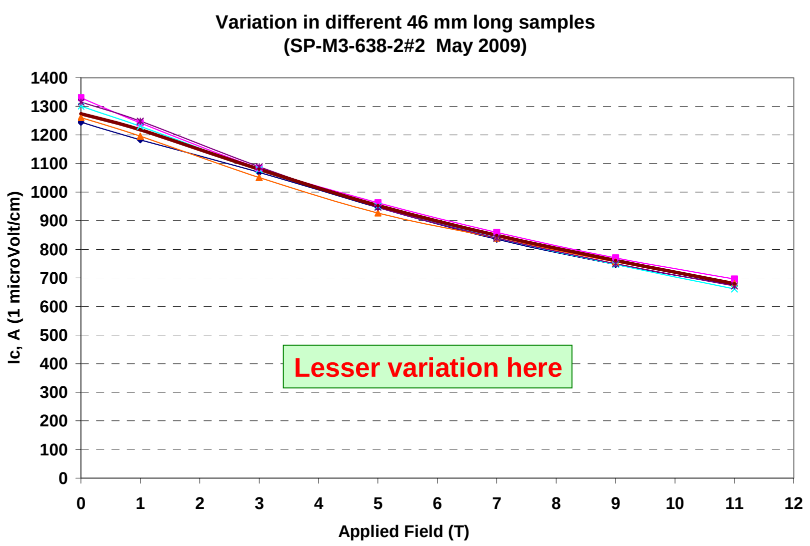


~175 A (77 K, self field)

~100 A (77 K, self field)


Variation in ~46 mm pieces from the same spool (SP-M3-638-2#2 May 2009)

Significant variation


Variation in different 46 mm long samples (SP-M3-638-2#2 May 2009)

Lesser variation here

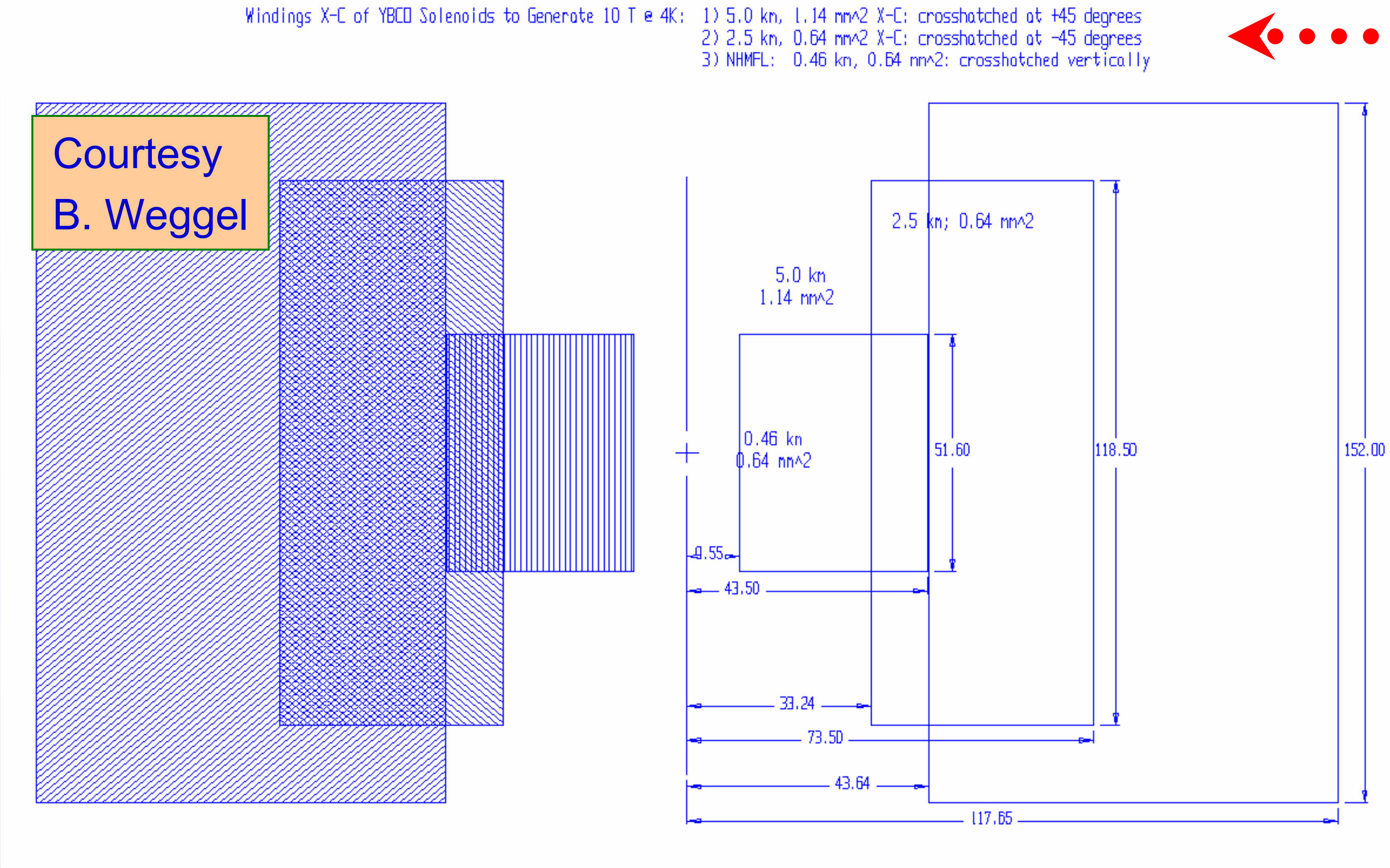
- Wire chemistry influences field dependence.
- At this stage of the production, there could also be a significant variation along the length at higher fields even though there was small at lower fields.

But what happens to the angular dependence?

How much is the difference in the minimum value?

Some tapes got damaged during high field testing.

10 T HTS Solenoid Designs



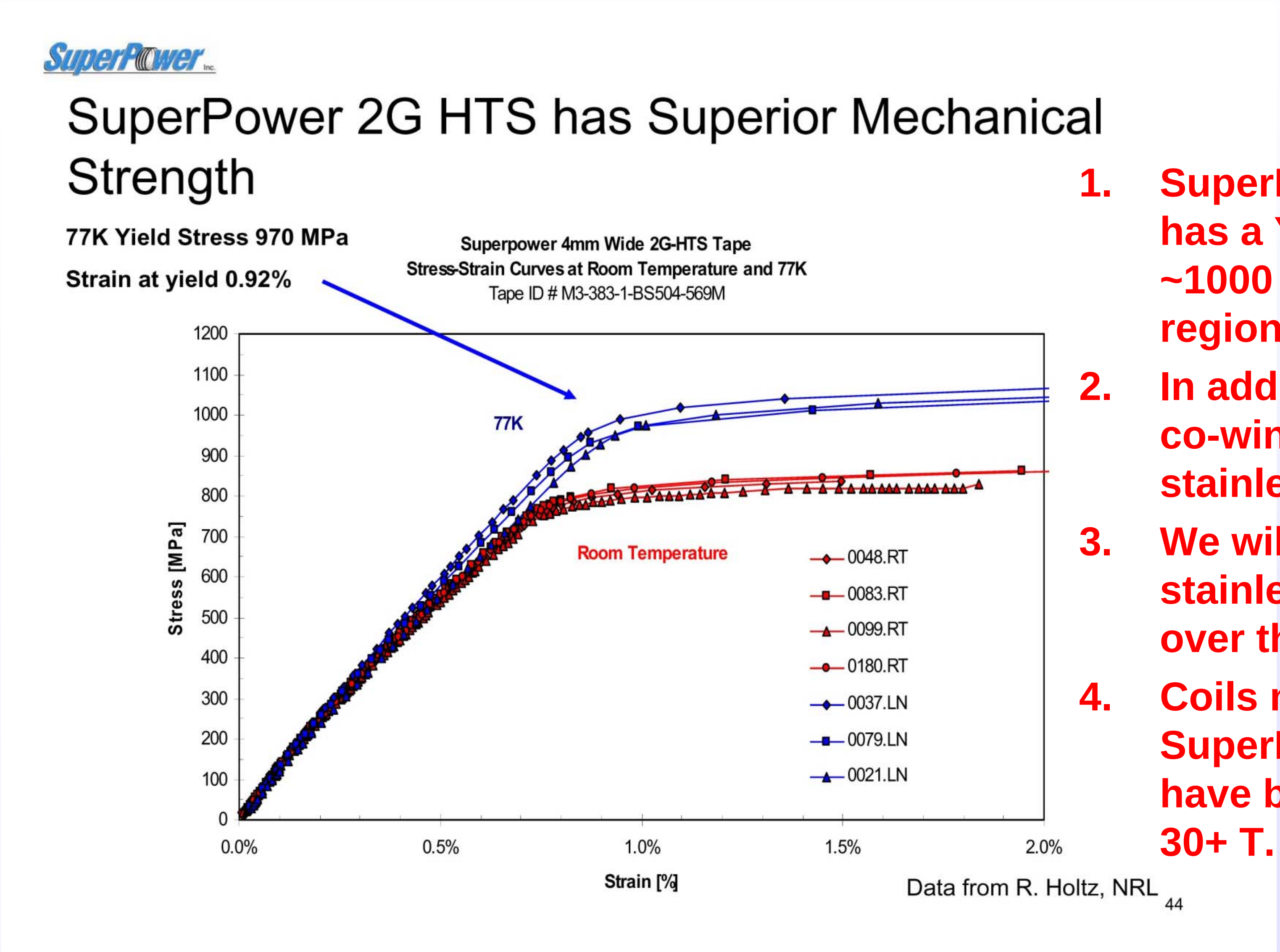
Courtesy
B. Weggel

**All cases for
10 T at 4.2 K**

- In the original SBIR proposal, we promised case (2) - which was for coil i.d. = 66.5 mm
  - o Case (1) was for coil i.d. = 87.2 mm
  - o Case (3) 9.8 T SuperPower/NHFML solenoid was for coil i.d. = 19 mm

Thanks to better Je, we are now aiming for a significantly higher value: ~100 mm coil i.d.

Higher Strength at Lower Temperature



SuperPower

SuperPower 2G HTS has Superior Mechanical Strength

77K Yield Stress 970 MPa

Strain at yield 0.92%

Superpower 4mm Wide 2G-HTS Tape
Stress-Strain Curves at Room Temperature and 77K
Tape ID # M3-383-1-BS504-569M

Data from R. Holtz, NRL

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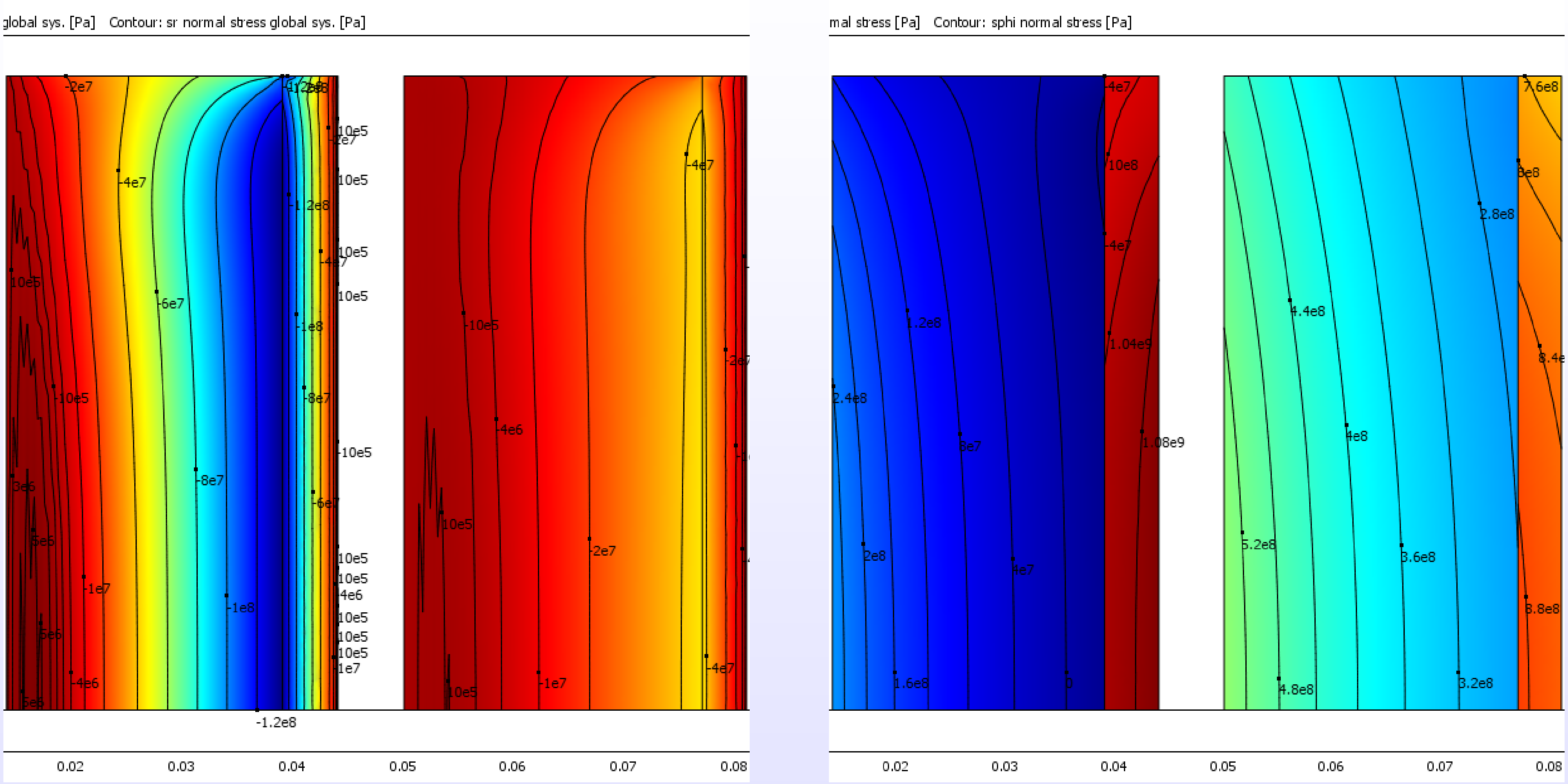
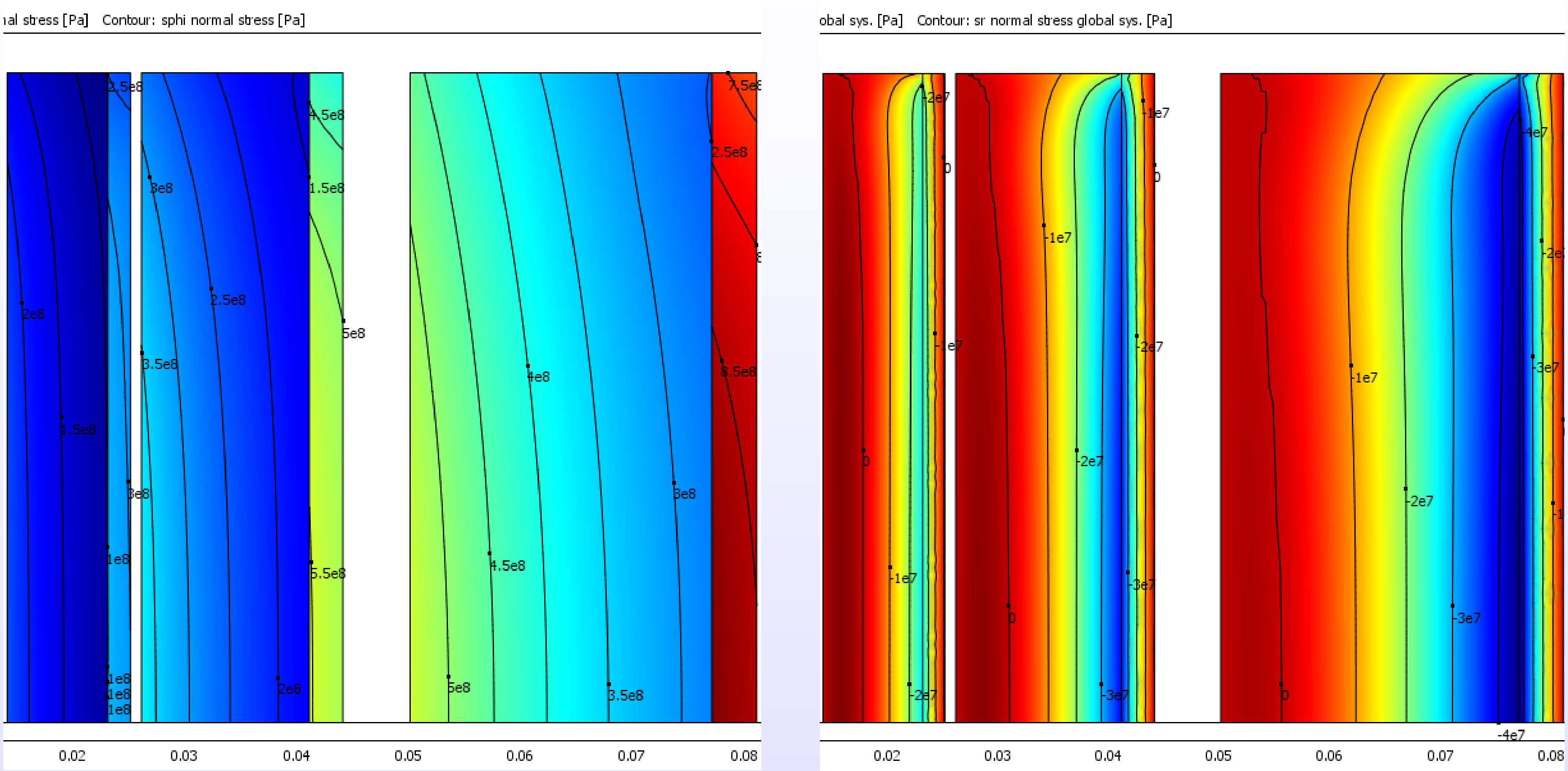
1. **SuperPower Tape has a Yield Stress of ~1000 MPA at the region of interest.**
2. **In addition we will co-wind with stainless steel tape.**
3. **We will also have stainless steel wrap over the coils.**
4. **Coils made with SuperPower tape have been tested at 30+ T.**

Current Design



σr [Pa] (left) and σφ [Pa] (right) stresses in magnets with 1 GPa pretension in inner-magnet banding.

Radial Segmentation



σφ [Pa] (left) and σr [Pa] (right) stresses in magnet banded with Eband = 3 Econd.

Correlation between Coil I_c and Wire I_c at 77 K